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Investigation of indoor thermal comfort in warm-humid conditions at a German climate test facility

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ABSTRACT

As a result of climate change outdoor temperature and humidity are predicted to increase within the next decades in Germany, especially in the Upper Rhine area. As indoor summer conditions will be affected by this change, responses of 136 subjects to warm-humid conditions have been investigated in a test-facility at the Karlsruhe Institute of Technology (KIT). Nine experimental conditions with high operative temperature (t_o) and different relative humidity (RH) levels (26 °C, 28 °C or 30 °C combined with 50%, 65% or 80%) were scheduled, with each participant experiencing two of the possible combinations. In contradiction to the German addendum of the European standard EN 15251, where a single upper limit for humidity ratio (HR) of 11.5 g/kg is recommended in summer, results indicate that human responses are additionally dependent on current temperature and other factors like thermal history. A linear regression model using operative temperature and humidity ratio is shown to describe the percentage of acceptability and is used to derive an extended comfort zone for seated activity in summer conditions (met = 1.1 and clo = 0.5). Thermal acceptance is compared to other studies (using effective temperature) and proves to be significantly lower with the German subjects than with participants who are adapted to a hot-humid climate. PMV shows underestimation of thermal sensation at elevated air humidity, up to 0.5 scale points under certain conditions.

1. Introduction

Nowadays in the Upper Rhine area, which is located in the south-western part of Germany, warm-humid periods already occur during summer. With the predicted general rise of moisture in the atmosphere [1] and more extreme summer temperatures due to climate change [2] [3], those warm-humid conditions will have an increasing effect on peoples' comfort in buildings. The objective of a sub-task in a German research project [4] is to define suitable upper humidity limits in residential buildings for a future summer climate. Against this background, comfort criteria at high indoor temperature and elevated air humidity are researched in literature and standards, and are then examined through experiments in an indoor climate test facility [5].

1.1. Studies of indoor comfort at elevated humidity and temperatures

Germany has a temperate climate and according to Köppen-Geiger [6] comprises mainly two climate zones. The western part is moderately warm and humid and has an “ocean climate” (Cfb). The eastern part is located in an area of humid continental climate (Dfb). The term “humid” is related to precipitation and not directly to the humidity of the air. Nevertheless since the 1920s German scientists were dealing with the question of defining boundaries of sultriness (in German: “Schwüle”) [7] and of charting areas of high temperatures and air humidity in Germany [8,9]. Most studies concern outdoor climate, and little literature can be found related to indoor comfort under warm and humid conditions.

Germany's situation is clearly different than that of large countries like the United States and China, which spread over many climate zones and also comprise hot-humid areas, or countries like Japan and Indonesia, which are mostly hot and humid in summer. In the United States research on the impact of humidity on the human comfort sensation started in 1923 with Houghton and Yaglou [10]. In the following decades different indices for rating the outdoor and indoor climate were developed, including the influence of humidity. Humiture in 1937 [11] and wet-bulb globe temperature of 1957 [12] are just two examples. An essential step forward for indoor comfort was taken by P.O. Fanger in Denmark. He had conducted his climate chamber experiments in the 1970s up to a relative humidity of 70% and included humidity as one factor into his well-known PMV model [13]. Further Danish experiments, which tested relative humidity up to 90% at the end of the 1990s, seem to be the only ones of that kind in western Europe so far.

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Table 1
Laboratory experiments on warm-humid and hot-humid conditions since 1998.

Year	Country	Source	Temperature	Humidity	clo	met	Participants
1998	Denmark	[18]	T_{air} 18, 23, 28	30, 50, 70%	n.a.	n.a.	40
1998	Denmark	[19]	T_{air} 18, 23, 28	30, 50, 70%	n.a.	n.a.	32
1998	Denmark	[20]	T_{air} 22.5, 25, 25.5	50, 80%	0.63, 0.9, 1.3	sedentary	n.a.
1998	Denmark	[21]	T_{air} 20, 23, 26, 29	35-90%	0.5	sedentary	38
1999	USA	[22]	et 20-26 °C	60-90%	0.5/0.9	n.a.	n.a.
1999	Japan	[23]	T_{air} 27 °C, panel 17–27 °C	45, 65, 85% RH	0.7	1.0	48
2005	Singapur	[24]	n.a.	HR 7.5–19.5 g/kg	n.a.	n.a.	32
2007	Japan	[25]	T_{air} 30 °C/SET* 25.2 °C	70% RH/30, 40, 50, 70% RH	0.67	1.2	12 adults
2013	China	[26]	T_{air} 26, 28, 30 °C	40, 60, 80% RH	0.3	“sitting quietly”	10 females, 10 males
2013	China	[27]	T_{air} 32, 36, 40	40, 60, 90% RH	0.5–1.2	> 1.2 (light, moderate, heavy work)	5 male students
2013	USA (Chinese participants)	[28]	T_{air} 26, 28, 30 °C	60, 80% RH	0.5	sedentary	8 females, 8 males
2015	USA (Chinese participants)	[29]	T_{air} 26, 28, 30 °C	60, 80% RH	0.5	sedentary	8 females, 8 males
2016	China	[30]	T_{air} 20, 23, 26, 29, 32	50, 70% RH	0.57	1.0	60
2017	China	[15]	T_{air} 20, 23, 29, 32, 36	50, 70, 90% RH	0.57	1.1	15 females, 15 males

Fountain et al. [14] provide an overview of experiments related to humidity and indoor comfort until 1996 and recently Jin et al. [15] summarized relevant studies in this scope.

Table 1 and Table 2 supplement those overviews and additionally provide parameters of the experimental conditions. Most of the field studies in hot-humid climates measured humidity, but did not provide special analysis of its impact. Therefore, Table 2 only lists the studies in which humidity played an essential role. The ASHRAE RP-884 database [16] had no special focus on hot-humid climates, but its widespread data comprises buildings from all climate zones: cold-dry to hot-dry and hot-humid. A re-analysis of this database had been conducted with regard to humidity [17].

1.2. Normative regulations of upper air humidity limits

In the ASHVE/ASHRAE standards the upper humidity limit for air-conditioned rooms has changed repeatedly throughout the last decades. Relative humidity (ASHVE 1915, 1932, 1938; ASHRAE 1966, 1992), wet bulb temperature (ASHVE 1920; ASHRAE 1992a) and humidity ratio (ASHRAE 1974, 1981, 2004, 2010, 2013) have been used as indices. The wet-bulb temperature is defined as the state of a certain amount of air, cooled down to saturation by evaporation of water and the latent heat provided by this amount of air itself. Humidity ratio (HR) is a measure of absolute air humidity and indicates how much water vapor is dissolved in 1 kg of dry air. The current definition in ASHRAE 55-2017 [34] continues using a humidity ratio of 12 g/kg. This limit is relevant, if the “Graphic Comfort Zone Method” (two comfort zones for 0.5 and 1.0 clo in relation to operative temperature and humidity ratio) is applied. If the “Analytical Comfort Zone Method” is used, summer clothing and seated person assumed, humidity ratio values up to 20.9 g/kg (at 0.1 m/s air velocity and t_o = 25.7 °C) and up to 21.7 g/kg respectively (at 0.2 m/s and 26.3 °C) are allowed for not exceeding a ratio of 10% dissatisfied (PPD according to Fanger). In many other countries, which have not authored their own regulations, the ASHRAE standard is used.

Whereas the ASHRAE now allows elevated humidity under certain conditions, the European and German standards are still more restrictive. Current specifications of an upper limit for air humidity from the perspective of indoor summer comfort can be found in DIN EN 15251 [35]. This European standard defines criteria for indoor room climate, which have to be applied for dimensioning and energy demand calculations as well as for performance and operation. It refers to ISO 7730, but criticizes that its definitions are mostly aiming to dimensioning of building facilities. EN 15251 therefore aims to provide criteria for a whole year assessment of the indoor thermal climate and includes an adaptive approach for naturally ventilated buildings (i.e. buildings without mechanical cooling). Many parameters are listed according to three building classes I, II and III (which correspond to A, B and C of ISO 7730). Accordingly, the upper relative humidity limits of 50% RH, 60% RH and 70% RH for dehumidification are recommended. Additionally and regardless of temperature and building class the general European version limits the humidity ratio to 12.0 g/kg whereas the German national annex specifies 11.5 g/kg and 65% RH, respectively. In the German standard DIN 1946 part 2, which had been published in 1994 and withdrawn in 2005, the same two values (11.5 g/kg and 65% RH) were described as upper limits for comfort. The subsequent standard EN 13779 [36] mentions a “summer maximum value” for “absolute humidity” of 12 g/kg, which means humidity ratio as well. All standards described above lack in specifications for buildings without mechanical ventilation or air-conditioning (i.e. the majority of German residential buildings). A specific “sultriness limit“ is mentioned in the VDI guideline 2089 [37], but it applies to indoor swimming pools and the unclothed human body, with a limit of water vapor pressure set to 22.7 hPa. That corresponds to a humidity ratio (called “water content” in the guideline) of 14.3 g/kg. This figure is called “empirical” and is allowed to be exceeded if the humidity ratio of the outdoor air passes 9 g/kg.

Against this background the present study investigates the responses

Table 2
Field tests on warm-humid and hot-humid conditions since 1997.

Year	Country	Source	Temperature	Humidity	clo	met	Participants
1997	Worldwide	[17]	T_{air} 24.7–34.2 °C	20.9–97.8% RH	0.2–1.1	0.8–2.6	1682
2004	Thailand	[31]	n.a.	13.3–22.6 g/kg	0.54–0.55	sedentary	288
2004	Singapore	[32]	n.a.	16.8–20.8 g/kg	n.a.	Residential	538
2004	Indonesia	[32]	n.a.	15.5–21.0 g/kg	n.a.	Residential	525
2013	Australia	[33]	n.a.	n.a.	n.a.	Office Work	6

Fig. 1. The test facility LOBSTER from outside.

Fig. 2. View into one of the two offices at LOBSTER.

of a large group of German participants to determine if a humidity ratio limit of 11.5 or 12.0 g/kg is suitable or if more diversified comfort criteria can be defined. Results are also compared to calculation methods (e.g. PMV) defined in the standards.

2. Experimental methods

To investigate occupant's comfort at temperatures and air humidity above the usual comfort zone experiments were performed in the test facility LOBSTER (Laboratory for Occupant Behavior, Satisfaction, Thermal comfort and Environmental Research) [38] at the Karlsruhe Institute of Technology (KIT). After pilot tests with 28 participants in 2015, main experiments with a total of 136 participants have been conducted in summer 2016 (May until October). Participants were recruited via the Internet and a local weekly paper and were remunerated afterwards. Two age groups (18–32 years and 50+ years) took part, and both groups were comprised of both female and male participants. In 2017 a final series of summer experiments is conducted. All experiments had been approved by the ethics and the data protection commissions of KIT.

2.1. Test facility

The LOBSTER (Figs. 1 and 2) contains two identical office rooms with a floor area of 24 m^2 each, in which five surfaces can be separately conditioned between 16 and 34 °C. The façade wall can not be heated or cooled, but it is highly insulated and equipped with 3-pane glazing. In addition to the thermal control of the surfaces, supply air from the trench heaters below the windows can be chilled or heated. In each room a humidifying function was established by mobile evaporative humidifiers. As their integrated control is not able to generate exact levels of relative humidity an on-off-control consisting of remote plugs was set up, which are operated according to the humidity sensors of the building control system. As LOBSTER can be rotated, the offices were positioned facing North to prevent the sun from directly shining onto the subjects during the experiments.

2.2. Experimental design

After acclimatization for 30 min in the vestibule, each participant experienced one out of nine combinations of operative temperature (26, 28, 30 °C) with relative humidity (50, 65, 80%) for 1 h, followed by another of those combinations for another hour (Fig. 3). Those nine conditions range from 10.5 to 21.5 g/kg, so that they span across the subject of investigation (11.5 and 12.0 g/kg) and enable evaluation of responses at the rather upper border of summer comfort. Different publications pointed out that humidity would only matter at elevated temperatures. Therefore three fixed relative humidity levels were chosen at three different temperature levels.

Comfort parameters (concerning thermal, humidity, and air quality aspects) were recorded in each room after 0, 15 and 30 min in a short questionnaire and after 60 min in a detailed questionnaire. The control was set to operative temperature so that surface temperatures and air temperature were always close together. The subjects were instructed to wear their own cotton summer clothes to avoid any irritation by strange clothing on one hand and synthetic materials on the other hand. They were sitting at a desk (met 1.1) and in the intervals between surveys they were allowed to perform individual activities (learning, reading, etc.). The participants were instructed not to drink during the hour or to drink only a small amount. Eating was not allowed.

Table 3 gives an overview of the scales used in the questionnaires. The numbers were not visible to the respondents, but were only used internally for evaluation. The planned conditions and achieved values (mean value and standard deviation) are listed in Table 4. For the following analysis only the 60 min votes of the first exposure have been taken into account. The available number of votes in each of the nine conditions is provided in column "N".

2.3. Measuring equipment

Physical parameters in each room were recorded by Ahlborn comfort meters every minute, including air and globe temperature, air velocity and air humidity at a level of 1.1 m above ground, possibly close to the subject. From the globe temperature radiant and operative

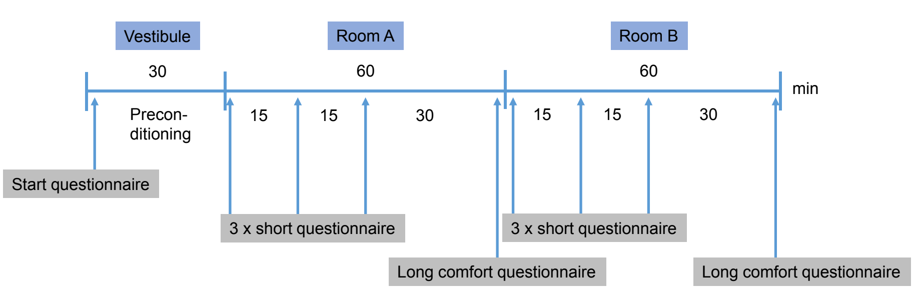

Fig. 3. Experimental timetable (intervals in minutes).

Table 3
Discrete comfort scales applied in the experiments (Thermal Sensation Vote – TSV, Humidity Sensation Vote – HSV, Thermal Preference Vote – TPV, Thermal Comfort Vote – TCV, Thermal/Humidity Acceptance Vote – TAV/HAV).

TSV		HSV		TPV		TCV	
+3	Hot	+3	Very humid	+2	Warmer	0	Comfortable
+2	Warm	+2	Humid	+1	Slightly warmer	−1	Just comfortable
+1	Slightly warm	+1	Slightly humid	0	No change	−2	Just not comfortable
0	Neutral	0	Neutral	−1	Slightly cooler	−3	Not comfortable
−1	Slightly cool	−1	Slightly dry	−2	Cooler		
−2	Cool	−2	Dry				
−3	Cold	−3	Very dry				
TAV/HAV							
0							Acceptable
−1							Just acceptable
−2							Just not acceptable
−3							Not acceptable

Table 4
Achieved physical parameters within the nine conditions created in the first room entered by the participant (mean value with standard deviation in brackets).

Combination	N	Operative Temperature [°C]	Relative Humidity [%]	HR [g/kg]	Air velocity [m/s]
26/50	15	26.0 [± 0.1]	52.2 [± 0.4]	11.1 [± 0.1]	0.09 [± 0.01]
26/65	17	26.1 [± 0.1]	64.9 [± 0.4]	14.0 [± 0.1]	0.09 [± 0.00]
26/80	12	25.9 [± 0.1]	79.2 [± 0.5]	16.9 [± 0.2]	0.12 [± 0.01]
28/50	15	28.0 [± 0.1]	52.7 [± 0.4]	12.6 [± 0.1]	0.08 [± 0.01]
28/65	17	28.0 [± 0.1]	64.5 [± 0.3]	15.6 [± 0.1]	0.13 [± 0.03]
28/80	16	27.8 [± 0.1]	78.3 [± 0.5]	18.8 [± 0.2]	0.09 [± 0.01]
30/50	11	29.8 [± 0.1]	50.9 [± 0.3]	13.6 [± 0.1]	0.09 [± 0.02]
30/65	17	30.1 [± 0.1]	64.6 [± 0.2]	17.6 [± 0.1]	0.08 [± 0.01]
30/80	16	29.8 [± 0.1]	75.9 [± 0.8]	20.4 [± 0.2]	0.09 [± 0.00]

temperature were calculated using the R-package “comf” [39]. Beside those standard comfort parameters the CO_2 concentration was measured in both rooms. As physiological parameters the heartrate, skin humidity, and skin temperatures have been recorded. Heartrate was monitored by Suunto heart rate belts and recorded in 1 s intervals. In one group of the participants skin temperature was measured at forehead, neck, right shoulder blade, left back of the hand and right shin, using iButton Thermochrons [40]. In the other group iButtons with temperature and humidity sensors (Type DS1923) have been used to measure skin temperature und air humidity 3 mm above the skin for calculating skin wettedness. They were located at the forehead, the left back of the hand, the chest, the dorsum and the right thigh. iButton data were recorded every minute. After 60 min spot measurements with an infrared thermometer and a corneometer (both from Courage + Khazaka electronic) were taken at one group for comparison with the iButton data.

3. Results

Responses of the participants have been analyzed with a focus on the relation to humidity ratio (HR), as this is the figure used in the standards (cf. 1.2). In combination with operative temperature (t_o) as a second independent variable, good correlations were found in regression models. As different authors had suggested to use modified effective temperature (et) or enthalpy for regarding effects of elevated temperature and humidity, those were also taken into consideration. Standard PMV and PPD (ISO, Fanger) respectively have been included, too. Those indices were also calculated through the R package “comf”, using the individual parameters (radiant temperature, air temperature, air humidity, air velocity and clo value) from the experiments. The metabolic rate was generally assumed to be 1.1 met. Unless specified differently, for the following results only those votes of the 136 participants were used, which had been provided at the end of the 60 min period in the first room.

3.1. Thermal sensation

The thermal sensation vote was surveyed on a 7-point-scale (cf. Table 3). Operative temperature alone shows a good correlation with thermal sensation vote (Table 5). If humidity ratio is included, the model significantly improves and the coefficient of determination rises to 0.402, with the single votes regarded. The correlation with HR alone is significant, but then R^2 is much lower. Fig. 4 provides a graphical representation of the derived model.

If the model is used for checking the maximum HR to achieve a thermal sensation vote of 0.5, we calculate 16.4 g/kg for an operative temperature of 26 °C and get 11.2 g/kg if t_o is 28 °C. For a vote of 1 (“slightly warm”) the upper limit would be 21.4 g/kg with t_o = 26 °C and 16.2 g/kg with t_o = 28 °C.

The validity of PMV has been the subject of several studies. One of importance was published by Humphreys and Nicol [41], where the authors analyzed the ASHRAE database and came to the conclusion that PMV overestimates TSV starting from relative humidity larger than 70%. This is contradictory to results of this study. Fig. 5 shows box plots (min, max, median, 25% + 75% percentiles) for the difference between calculated PMV and the actual vote of the respondent. PMV was calculated based on the actual clothing of each participant - once without chair and once with the chair included (+0.1 clo). If the value is lower than zero, the PMV underestimates the thermal sensation. That is especially the case for the test conditions with 80% relative humidity.

3.2. Thermal acceptance

Participants were asked to rate their acceptance of temperature (TAV) on a 4-point-scale with two options marking the acceptable range (“just acceptable” and “acceptable”) and two options for negative

Table 5
Overview of linear regression results for TSV based on different variables.

Variable	272 single votes		Votes averaged in 9 conditions	
	R^2 adjusted	Sign.	R^2 adjusted	Sign.
t_o	0.382	0	0.872	0.0001
HR	0.183	0	0.299	0.0737
t_o HR	0.402	ANOVA 0.0015	0.936	ANOVA 0.0299
PMV	0.360	0	0.917	0
et	0.395	0	0.925	0
Enthalpy	0.256	0	0.505	0.0193

acceptance ("just not acceptable" and "not acceptable"). Fig. 6 presents the percentage distribution of the votes for the nine test conditions. It shows that acceptance of at least 90% was achieved with two 26 °C conditions (humidity ratio at 11.1 and 14.0 g/kg). With 16.9 g/kg at 26 °C and 12.6 g/kg at 28 °C, still more than 80% of the participants rated the temperature "acceptable" or "just acceptable" – this is at rather high humidity values. Above 28 °C and 15.6 g/kg 80% of acceptance could not be reached.

When analyzing for the nine conditions the percentage of participants (average per category), who rated the temperature to be acceptable (i.e. "acceptable" and "just acceptable"), a good linear regression model for predicting the percentage could be found, using operative temperature and humidity ratio as independent variables. The

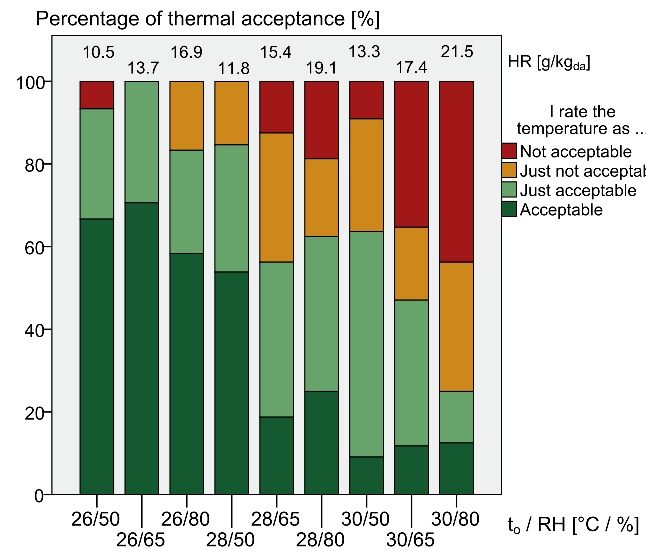

Fig. 6. Percentage of thermal acceptance votes for the nine test conditions [t_o/RH].

coefficient of determination is $R^2 = 0.895$ and the predicted percentage of thermal acceptability (abbreviated as "PTA") can be calculated by the following formula:

$$PTA[\%] = 373.859 - 8.714^{*} t_o - 3.959^{*} HR \quad (1)$$

with t_o – operative temperature [°C]

HR – humidity ratio [g/kg$_{dry\ air}$]
$t_o \geq 26$ °C and HR > 10 g/kg$_{dry\ air}$
$t_o \geq 31.472 - 0.454 * HR$

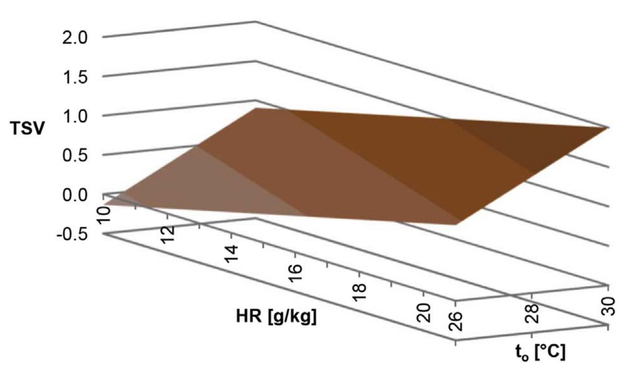

Fig. 4. Derived model for prediction of TSV with operative temperature (t_o) and humidity ratio (HR) as the independent variables, displayed as a 3D-diagram.

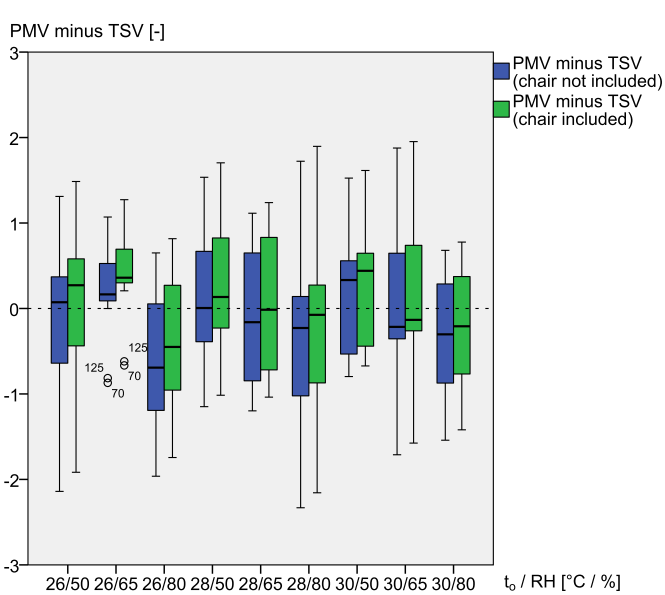

Fig. 5. The difference of real thermal sensation vote (TSV) and PMV, with and without chair included in the clo-value, categorized by the nine test conditions.

3.3. Humidity sensation

On a 7-point-scale, participants had also been asked to rate their sensation of humid air. Though the human being has no direct sense to feel air humidity, it is supposed that by respiration, the feeling of mucous membranes (nose, mouth), and perceived dryness of the eyes (retina) people can differ low from high humidity.

Accordingly a relatively wide spread is recognized within the humidity sensation votes at every level of humidity ratio (Fig. 7). The coefficient of determination is only 0.227 and even between 18 and 20 g/kg we find votes of "slightly dry" and "dry". However, the trend is evident. Relative humidity was also tested as a predictor, but the

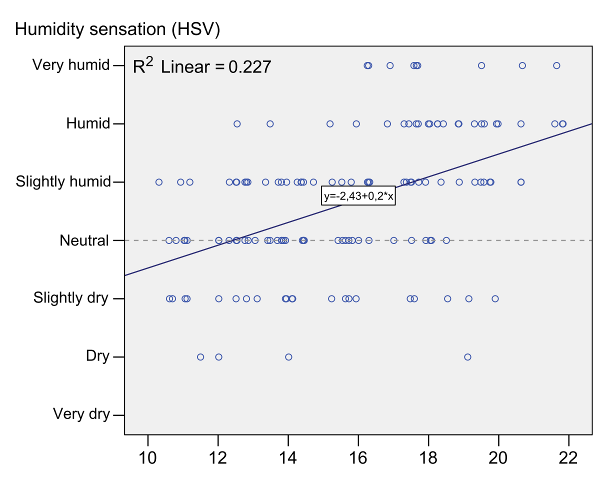

Fig. 7. Humidity sensation votes (7-point-scale) related to humidity ratio.

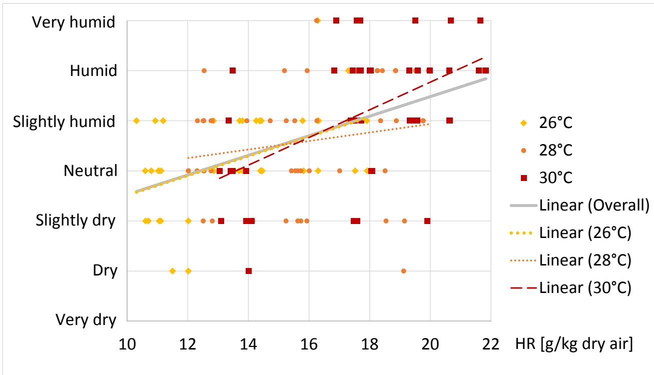

Fig. 8. Humidity sensation votes (7-point-scale) related to humidity ratio, separated by the three temperature levels of the experiments.

relation was much smaller (R^2 = 0.143).

For testing a possible influence of temperature level on the strength of perceiving air humidity, the regression lines were separated by the three different temperature levels 26°, 28° and 30 °C (Fig. 8). The slope of the regression line for 26 °C is almost identical to the overall regression line and quite similar to the one at 30 °C. The slope of the regression line at 28 °C is smaller. When regarding the single coefficients of determination a clear difference between 28 °C (R^2 = 0.038) and 30 °C (R^2 = 0.285) can be stated. Nevertheless, with 26 °C R^2 is 0.226. From the available data no significant relation between temperature level and sensitivity towards air humidity can be concluded.

3.4. Humidity acceptance

Analogous to the thermal acceptance question, a 4-point-scale has been used for questioning the rating of humidity. In general a decrease of the acceptance with rising air humidity can be stated. Fig. 9 shows that in most of the situations the percentage of acceptable votes is lower than the temperature acceptance.

When building a linear regression model for predicting the percentage of acceptability by the humidity ratio (average values of the nine conditions as a base), combining the two votes “Just acceptable” and “Acceptable” leads to better results (R^2 = 0.600) than using them separately (“Just acceptable”: R^2 = 0.073, “Acceptable”: R^2 = 0.312). It seems to be difficult for the participants to distinguish their

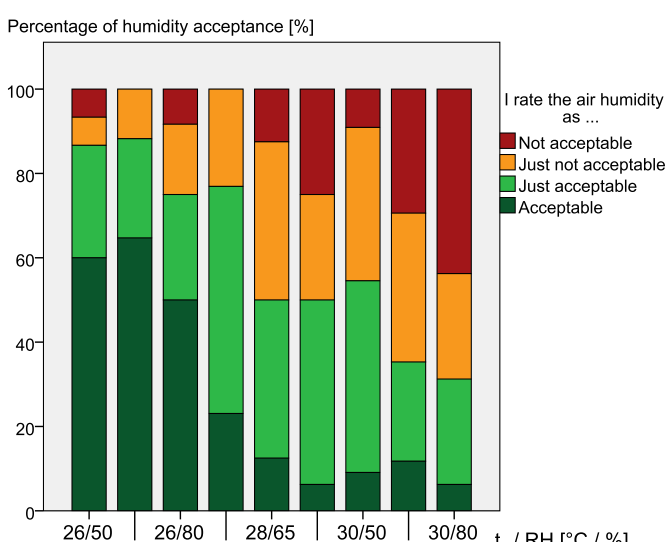

Fig. 9. Percentual distribution of humidity acceptance vote within the nine tested conditions.

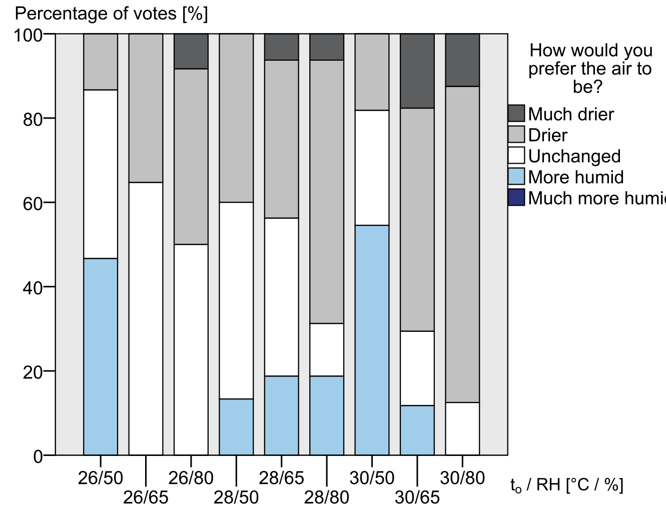

Fig. 10. Percentual distribution of humidity preference vote within the nine tested conditions.

expression of satisfaction into those two terms. However, if the operative temperature is included into the model for the combined votes, it improves significantly (R^2 = 0.934, t_o sign. at 0.002, HR sign. at 0.005). The acceptance of humidity is mainly influenced by the temperature.

Fig. 10 shows the proportion of the preferred air humidity grouped by the nine conditions. The vote “Much more humid” was never chosen, but the vote “More humid” has a share in six of the nine groups. It was chosen at all 50% RH conditions (46.7% at 26 °C, 13.3% at 28 °C, 54.5% at 30 °C) and at two 65% RH conditions (18.8% at 28 °C, 11.8% at 30 °C). Interestingly at 28 °C and 80% relative humidity there also was a share of 18.8% people voting “more humid”, which could only be explained through the natural diversity in the people's sensation. The option “Much drier” occurred at all 80% RH and at the two warmest 65% RH situations.

3.5. Perceived air quality

Different authors have already shown that air, which is warmer and more humid, is perceived as being of a lower quality [19] [42]. Polluted air was perceived as cleaner when it had a lower temperature. On a continuous scale (internally evaluated from 0 = “bad” to 100 = “good”) the respondents were asked to mark their perception. In all tested conditions, we find a large spread of the selected values (Fig. 11). At all levels of temperature, the influence of the air humidity can be clearly stated, with only condition 30°C/80% RH being off the trend. The coefficient of determination for a linear regression model using HR to predict the perceived air quality is quite low at R^2 adj. = 0.116 if the single votes are used (Table 6). Models using t_o (R^2 adj. = 0.175) or PMV as a predictor (R^2 adj. = 0.195) range in a higher level of precision. While HR and air velocity (V_{air}) significantly improve the model, CO_2 concentration and other variables have been tested without showing any significant impact. The positive impact of air velocity on perceived air quality had been described by Zhai et al. [29] for example.

3.6. Comparison to other studies

As summarized in section 1.1 there have been different laboratory and field lab studies in several countries concerning warm-humid indoor conditions. In this section findings of this current study are compared to results of other studies, which provide relevant data in the corresponding publications.

In a recent study Jin et al. [15] tested 15 female and 15 male young

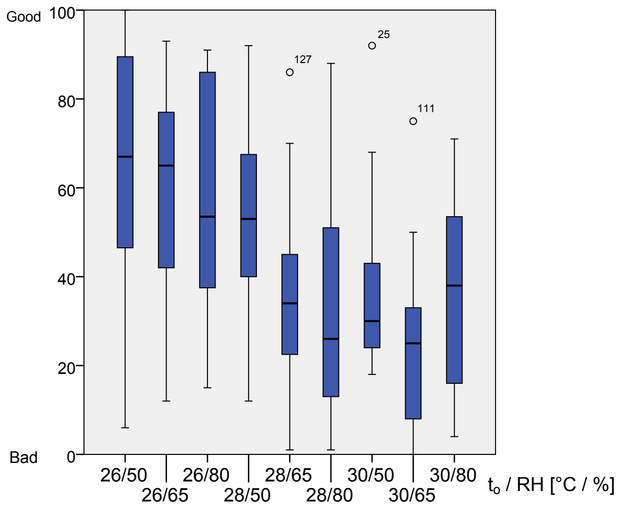

Fig. 11. Boxplot of the perceived air quality votes at the nine conditions.

Table 6
Performance indicators of a linear regression model predicting PAQ (perceived air quality) based on 136 single votes in the experiments.

Variable	R^2 adjusted	Significance level
CO_2 concentration	0.004	0.220
Relative humidity	0.017	0.074
Enthalpy	0.148	0.000
t_o	0.175	0.000
PMV	0.195	0.000
SET	0.189	0.000
HR	0.116	0.000
HR, t_o	0.193	Change of t_o: sig. 0.000
HR, t_o, V_{air}	0.211	Change of V_{air}: sig. 0.001

people who where born and raised in hot-humid areas of China. They used two temperature levels (29 and 32 °C) combined with 50, 70 and 90% relative humidity. Additionally two "cool" conditions (20 °C and 23 °C, both with 50% RH) and one "hot" condition (36 °C/45% RH) have been tested. Together with the situation in the preconditioning room they used 10 conditions in total. As the authors related their results to "new effective temperature ET*", the same index was calculated using [39]. Here it is just called effective temperature. Fig. 12 shows a remarkable difference between the subjects of the Chinese and this German study: with a rising effective temperature the acceptance of the subjects, who are acclimated to the mild European climate, decreases much faster. Whereas the percentage drops below 50% at about 30 °C, this value is passed at about 36 °C in the Chinese experiment.

In another study eight female and eight male students or researchers

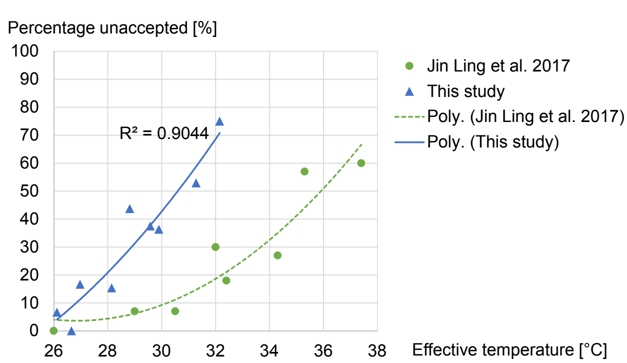

Fig. 12. Percentage of unaccepted in the study of Jin et al. [15] and this study, in relation to effective temperature.

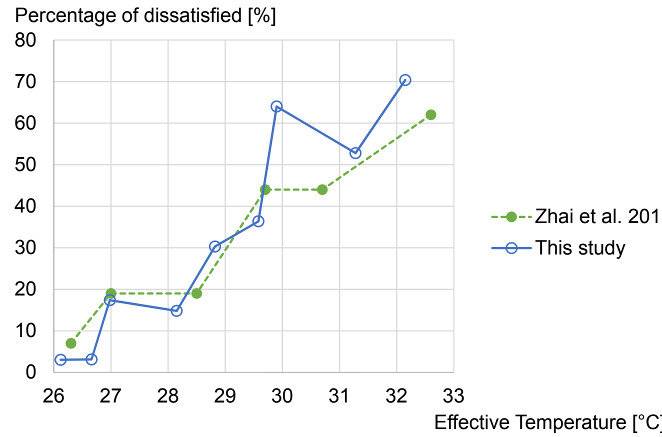

Fig. 13. Percentage dissatisfied in the study of Zhai et al. [29] (with no fan used) and this study (reversed acceptance), in relation to effective temperature.

from China were tested in a climate chamber at CBE of UC Berkeley [29]. Here again the related parameter is ET* and the focus of the study were different air velocity levels. However, it is possible to compare the percentage of dissatisfied participants when there was no fan (Fig. 13). In the lower range of effective temperature we see similar results, but with elevated temperatures and humidity the participants of this German study are reacting more sensitively again. Unfortunately, it is not written in Zhai et al. [29] which climate zone the Chinese participants came from and how long they had lived in the US.

4. Discussion

The results and findings above have shown that respondents accepted higher humidity ratios than 12 g/kg under certain circumstances. Their sensation and perception of air humidity is at least dependent of the current temperature. The ASHRAE 55 calculation method and many publications confirm that result. Within this section an extended comfort zone (compared to the German standards) will be presented. The experimental design and a comparison of thermal acceptance vote to other vote types are discussed. Finally the possible impact of seasonal adaptation is regarded.

4.1. Adapted comfort criteria

From the linear regression model presented in 3.2 a relation between operative temperature and humidity ratio can be defined, if the average PTA is fixed to a certain value. In Fig. 14 the corresponding lines for 90% and 85% are shown as solid lines. These target percentage

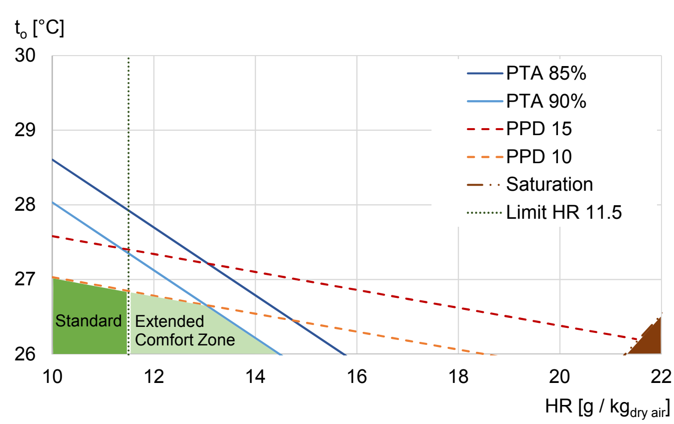

Fig. 14. The comfort zone up to a humidity ratio of 11.5 g/kg (Standard) and the extended comfort zone based on PPD (Fanger) and percentage of acceptance (PTA) from the experiments.

values were chosen according to EN 15251, where they are defined for the three building categories (cf. 1.2). For 90% acceptability the formula is:

$$t_o limit = (283.859 - 3.959^* HR)/8.714 [°C] \quad (2)$$

with $10 < HR < 16.91$ g/kg.

Likewise, the lines for PPD 10 and 15 according to Fanger are drawn as dashed lines. PPD has been calculated with clo = 0.5, met = 1.1, and air velocity = 0.1 m/s. At 10 g/kg the lines start with lower values and their slope is smaller, so that at certain points they are intersected by the PTA-lines, which have a steeper slope. As our experiments showed that PMV underestimates thermal sensation with high humidity values, we then use the solid lines as the criterion. The resulting extended comfort zone for 90% acceptability is shown as a gray area in Fig. 14. The difference to the criteria defined in the standards can clearly be seen. These comfort criteria are now used to evaluate building simulation results at warm and humid summer conditions.

For deriving the model and defining the extended comfort zone the percentage of acceptance has been used, because it was regarded as a direct expression of dissatisfaction by the participant. The respondents have been also asked for their thermal sensation, thermal preference, and thermal comfort, so that differences between the votes should be discussed.

For this purpose, linear regression models (using mean values of the nine conditions) were generated by using t_o and HR as variables and presented in Fig. 15. If TSV is 0.5 (the value between "neutral" and "slightly warm", which Fanger defined for the PPD 10% limit), the thermal acceptance vote ranges closer to "just acceptable" than to "acceptable". An acceptance vote of "just acceptable" (= -1) would correspond to a TSV of 0.83, and therefore be quite close to "slightly warm" (cf. Table 3).

The above findings show that including the vote "just acceptable" as a representation of the user's satisfaction is to some extent different from the PPD method. However, the difference is not large, but still it needs further investigation. This will be part of the ongoing project and extended by additional data from 2017 experiments.

4.2. Experimental design

A suitable experimental design is the base for reliable statistic results. Literature review showed that in warm-humid or hot-humid experiments exposure times from 20 min [19] across 60 min [15,26,30] and 120 min [20] [21] up to 180 [25] minutes have been used. It can be concluded that after 60 min only small changes occurred in the sensation and perception votes of the participants, whereas especially within the first 30 min the changes were larger.

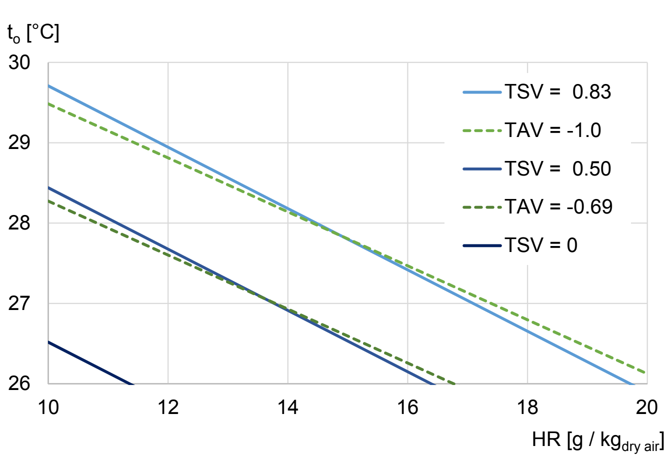

Fig. 15. Relation between t_o and HR causing votes TSV = 0.5 and TAV = -1 ("just acceptable") and comparison to corresponding lines.

In the presented experiments an exposure time of 60 min was defined. Whereas the thermal votes after 0, 15, and 30 min were significantly influenced by the condition before, with the 60 min vote there was only a small influence on the humidity sensation vote. The thermal sensation votes after 60 min did not show an interrelation to the condition before. The measurement of skin temperatures confirmed stabilization already after 30 min.

As in the experiments use was made of both available test rooms, two sets of questionnaire data exist for each participant (related to two of the nine temperature-humidity conditions). Due to statistical reasons, and to avoid the individual influence disturbing the models, the analysis at hand only uses data of the first 60-min periods ("between-subjects-design"). As the thermal votes after 60 min in the second period could be proved to be mostly independent from the situation in the first room, further work will regard including statistical analysis of both periods ("mixed/complex design").

4.3. Middle-term adaptation

The experiments were performed in summer 2016, but the overall time span lasted from mid-May until mid-October. Therefore, the several subjects experienced different climate conditions during the days before the experiment. Even though the experiments were conducted only during non-heating period in Germany, the running mean outdoor temperature [35] shows large variation from 8.5 °C to 23.7 °C, whereas the mean value is 18.7 °C (SD 4.0 °C). The impact of a preceding outdoor temperature was examined by linear regression modeling, using current operative temperature and humidity ratio in the room as the base variables. This time all single 60-min-votes of the participants instead of mean values were used. Including the running mean outdoor temperature improved the prediction of TSV significantly (ANOVA p-Value 0.006), whereas a simple arithmetic mean of the proceeding 7 days is in the same range (p-Value 0.005). An arithmetic mean of the proceeding 28 days performs better and is significant at 0.0001. Similar results are obtained for the humidity sensation vote (HSV): a model using the current humidity ratio in the room is improved by including a 4-week-mean of the outdoor humidity ratio ($p = 0.0009$).

An impact of thermal history of the participants exists in the data. However, the method of the adapted comfort criteria (cf. 4.1) does not yet include this influence. Based on additional experiments in 2017 it is planned to further investigate the role of preceding outdoor conditions and if possible, to include it into the model described above.

5. Conclusions

The presented experiments have extensively examined thermal comfort at warm temperatures combined with elevated air humidity. The key findings have been:

- The impact of air humidity is strongly dependent on the room (operative) temperature, so that an upper humidity limit should only be defined in combination with temperature
- An upper humidity limit for summer indoor conditions of 11.5 g/kg as defined in the German addendum of DIN EN 15251 should not be used
- A more diversified comfort criterion based on temperature and humidity ratio was proposed instead and the approach was explained
- The comparison of thermal acceptance from this study with other studies showed that ethnic origin and long-term adaptation play a role in the perception of warm-humid indoor conditions
- Even within this summer study middle-term adaptation to warmer outdoor conditions lowered the expressed thermal sensation of the participants
- Further investigation is needed to define the questionnaire category which should be used for deriving comfort zones, as differences between sensation, preference and acceptance ratings were found

- Responses of subjects not adapted to warm-humid conditions showed an underestimation of TSV by PMV at high air humidity

The results represent comfort criteria of persons who have been living in the Karlsruhe region for at least two years and who are adapted to the current climate conditions. But if the climate will change in the near future the question will be, how fast can the people adapt and to which extent will this adaptation influence their perception of comfort. The following issues should be addressed in future research:

- Subjects of the presented study were wearing their own cotton summer clothes. Further research could also address other materials to learn about the impact of water vapor diffusion through and storage within the clothing.
- For a better understanding of residential indoor comfort, field studies should be performed in the same climate zone and compared to the presented results. The advantage would be a more realistic setup where residents can go to another room or change their activity pattern. The disadvantage would be a low occurrence of temperatures above 28 °C and 65% relative humidity under current local climate conditions.
- Nevertheless, all described experiments did not take into account longtime exposure to warm-humid conditions, as the experiment time did not last longer than 3 hours. An important issue is the question, if longtime exposure exhausts the human body and the dissatisfaction will increase or if - through adaptation - the organism can better deal with the conditions and dissatisfaction will decrease.

In summer 2017 further experiments are conducted to enlarge the statistical sample. Extended results are expected to be published by the beginning of next year.

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